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TERRESTRIAL TEMPERATURE AND SOLAR CHANGES

By ELLSWORTH HUNTINGTON

During the past summer there have appeared two articles which are likely to play an important part in future investigations of the causes of climatic variations. Each is the summation of a long series of earlier studies. In one of the articles,[1] Köppen, with the aid of a large series of tabulations by J. Mielke, investigates the relation of changes in mean temperature to changes in the sun-spot cycle during the entire century from 1811 to 1910. This includes nine sun-spot cycles. The final conclusions are based upon averages derived from about 20,000,000 observations of temperature in all parts of the world. In the earlier years, only about 30,000 per year are available, but, toward the end, the number rises to 500,000. It will be practically impossible to extend the basis any wider for some years to come. All the available early materials seem to have been drawn upon. During later years it would be possible to utilize an even larger number of stations than has actually been done, but this would not influence the results, since the additional stations would be located near those already employed. The only great improvement upon Köppen's present work would be the inclusion of a much larger number of marine stations and of stations in remote regions not yet controlled by civilized man. That will not be possible for many years, so that the results now before us may be regarded as settling the question as far as any settlement is yet possible.

The other paper, by Arctowski,[2] employs a wholly different method. Instead of trying to utilize as many observations as possible, he has taken a smaller number and has investigated them intensively. His method is almost diametrically opposed to that of Köppen. Little attention is paid to averages, but very great attention is given to small variations from month to month and from place to place. Arctowski's method consists primarily of two things. In the first place, he eliminates the effect of the seasons by averaging first the twelve months from January to December of a given year, next the twelve from February of the same year to January of the succeeding year, then March to February, and so on. In each case he uses the average for twelve consecutive months and plots it in the middle of those months. Thus he gets curves showing the amount by which, in any given region, the temperature for each month departs from the normal for the period of ten years which he has undertaken to investigate. In addition to this he has plotted the monthly departures upon maps, and thus, for each month of the ten years, he has a map which shows just what parts of the country were above or below the normal temperature for that particular season. His method is in the highest degree intensive and geographic, while that of Köppen is extensive and mathematical. Since a period of only ten years is covered in Arctowski's present article, and of only ten more in previous articles where the data have been dealt with less fully, Arctowski's work does not attempt to deal with the eleven-year sun-spot cycle, but only with variations of shorter periods. Hence in every respect it differs from that of Köppen. Yet both authors agree in their final conclusion.

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[1] W. Köppen: Lufttemperaturen, Sonnenflecken und Vulkanausbrüche, *Meteorologische Zeitschrift*, Vol. 31, 1914, pp. 305-328.

[2] Henryk Arctowski: A Study of the Changes in the Distribution of the Temperature in Europe and North America during the years 1900 to 1909, *Annals of the New York Academy of Sciences*, Vol. 24, 1914, pp. 39–113.

They conclude that changes in the sun cause changes in the distribution of temperature upon the earth. Since the available data are derived from only a small part of the earth's surface—that is, from the inhabited lands, especially in Eurasia and North America, and to a less extent in the other continents and islands—they do not assert that the mean temperature of the earth as a whole varies from one part of a cycle to another, but they both appear to believe that this is probably the case.

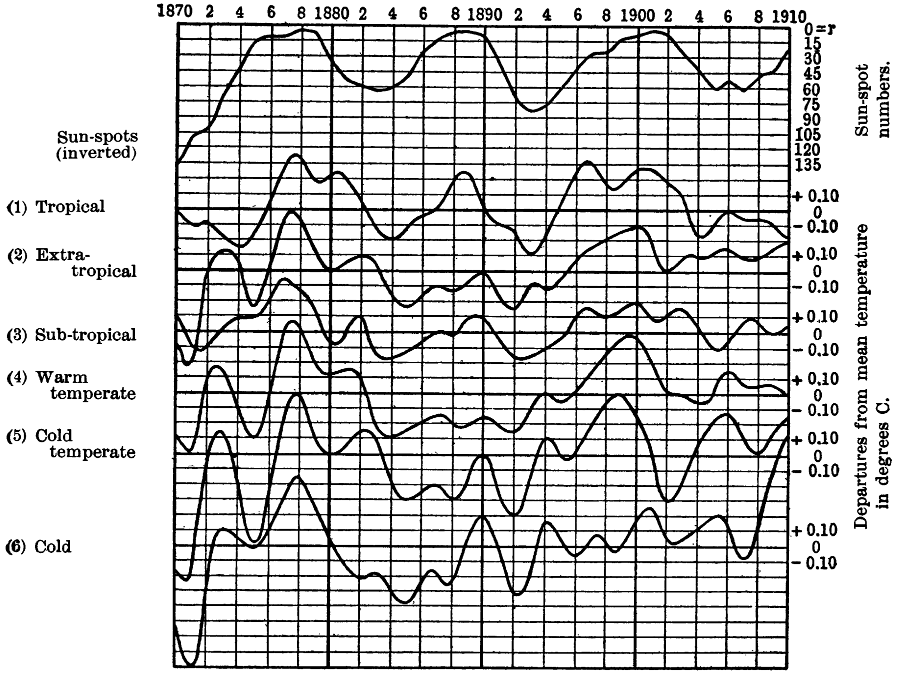

FIG. 1—Sun-spots and temperature, 1870 to 1910. After Köppen.

Köppen divides the world into twenty-five regions, which he again groups into (1) tropical and (2) extra-tropical. The latter includes the following zones: (3) subtropical, (4) warm temperate, (5) cold temperate and (6) cold. In his Figure 2, reproduced here as Figure 1, he plots the figures for these zones for 40 years below the *inverted* sun-spot curve. A little examination shows that the tropical curve agrees closely with the sun-spot curve, and the same is true of the subtropical curve, except that 1872 and 1873 are exceptional years, while the maximum of 1888-9 is delayed. Coming to the temperate zones the agreement is still visible but less marked, while in the cold zone there is agreement up to about 1877 and after 1906, but disagreement in the intervening period. This means that the following law seems to hold good: when sun-spots are numerous the temperature of tropical regions is lower than the normal, while as the number of spots decreases the temperature rises until it reaches its greatest excess above the normal at times when spots are least numerous. Outside the torrid zone this intimate relation between spots and temperature becomes less and less apparent, until it almost disappears in the far north. Köppen further finds that the greater the number of stations and the larger the number of years, the closer becomes the agreement. When he made his first investigations over forty years ago the temperature appeared to lag behind the spots, but with fuller data this lag almost disappears. The results for the entire period of one hundred years have been divided into a number of divisions, for which the smoothed curves shown in Figure 2 (Köppen's Figure 3) have been plotted. The unsmoothed figures for the upper two curves and the lower two curves are given in the accompanying table. In the figure the year "0" is equivalent to the "approximate year of sun-spot minimum" in the table.

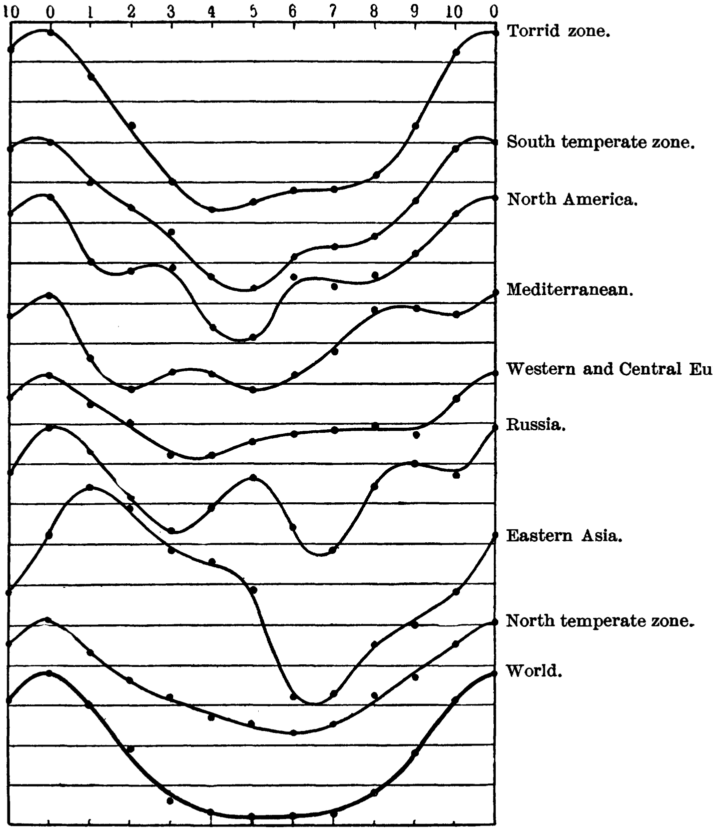

FIG. 2—Variations in temperature during the sun-spot cycle.

Departures from Mean Temperature during the Sun-spot Cycle*

Year of Sun-spot Cycle	Torrid Zone	South Temperate Zone	North Temperate Zone	World (lands)
Approximate year of sun-spot minimum....	0.36° C.	0.23° C.	0.31° C.	0.32° C.
1 year after minimum	0.11	0.08	−0.04	0.11
2 years after minimum........................	0.07	0.03	0.07	0.07
3 years after minimum........................	−0.11	0.03	−0.07	−0.08
4 years after minimum........................	−0.23	−0.20	−0.06	−0.13
5 years after minimum (=approximate year of sun-spot maximum)....................	−0.11	−0.20	−0.12	−0.14
6 years after minimum........................	−0.13	−0.03	−0.08	−0.11
7 years after minimum........................	−0.11	−0.08	−0.20	−0.16
8 years after minimum........................	−0.13	−0.04	0.07	−0.04
9 years after minimum........................	0.02	0.00	−0.04	−0.02
10 years after minimum........................	0.24	0.25	0.07	0.18

* Köppen does not use the exact sun-spot cycles, because their length varies. He employs a uniform period of slightly over 11 years. Hence the minima do not all fall in the first year of our table, but may fall a year or even two years earlier or later. This makes no difference in the general result, however, for if the actual years of sun-spot maxima and minima are used instead of Köppen's approximations, we find that the difference in temperature amounts to 0.44°C, instead of 0.46°C., as it now stands in the last column of the table.

The results obtained by Köppen are so consistent in various parts of the world, and agree so well with those obtained by other investigators, such as Newcomb, that it no longer seems possible to question the truth of the general law enunciated above. This at once brings up a most interesting question. To quote from Abbott (*Science*, Vol. 39, 1914, p. 347): ''It appears that the greater the number of sun-spots the higher will be the solar constant of radiation, and that an increase of a hundred sun-spots corresponds to an increase of about 0.07 calories per square centimeter in the solar radiation outside the earth's atmosphere.'' In other words, when sun-spots are especially numerous the sun's radiation increases in intensity, and the earth grows *cooler*. In a paper entitled ''The Solar Hypothesis of Climatic Changes'' in the *Bulletin of the Geological Society of America*[3], I have suggested that this striking anomaly may be due to an increase in convection at times of many sun-spots. Tropical hurricanes and the cyclonic storms of temperate regions both become more numerous at such times, and they may possibly carry so much warm air upward in the convectional movements of their centers that they appreciably lower the mean temperature of the earth's surface in the torrid and temperate zones, but not appreciably in the polar zones, where the centers of such convectional storms are rarely found. Increased activity of the sun may be the cause of the increased activity upon the earth. In this way, when sun-spots are numerous, the earth's surface may become cooler, the air near the present upper limit of convection may become warmer, and the level of the isothermal layer may be raised. The matter is too complicated for further consideration at this time.

When one sun-spot cycle is compared with another Köppen does not find reason to think that the mean temperature varies in harmony with the range of spottedness. That is, when the difference between the maximum and minimum spots of a given cycle is great, there does not seem to be a correspondingly great difference in the mean temperature. In support of this he gives the following table, which I have rearranged so as to place the sun-spot cycles in the order of their intensity:

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[3] Vol. 25, 1914, pp. 477–590.

FIRST YEAR OF SUN-SPOT CYCLE	DIFFERENCE BETWEEN MAXIMUM AND MINIMUM SUN-SPOT NUMBERS	DIFFERENCE BETWEEN TEMPERATURE AT TIMES OF MAXIMUM AND MINIMUM SPOTS		
		A NORTH TEMPERATE ZONE	B TROPICAL ZONE	C SOUTH TEMPERATE ZONE
1833	126	2.2	5.1	...
1867	126	−0.1	1.7	2.9
1844	115	0.5	1.5	2.2
1855	88	2.8	1.2	2.0
1889	80	0.6	2.4	1.7
1822	61	1.4	2.4	...
1878	59	1.8	2.1	1.3
*1811	45	3.2	...	...

* The data here are too scanty to be of much importance.

In the north temperate and tropical zones the table supports Köppen's conclusion, but in the south temperate zone the range of temperature decreases regularly in harmony with the decrease in range of spottedness. The north temperate and tropical zones contain large masses of land, and the figures for temperature represent the conditions as influenced by the varying intensity of winds from the ocean. The south temperate zone contains so little land that it may be regarded as representing marine conditions. If similar conditions are characteristic of the ocean as a whole—except in the parts where large bodies of heated water are brought in from other latitudes—the mean temperature of the entire earth must rise and fall in harmony with the sun-spots, not only when parts of the same sun-spot cycle are compared, but when different cycles are compared.

The last part of Köppen's paper is devoted to a discussion of the effect of volcanoes upon temperature. He comes to the conclusion that no important effect seems as yet to be proved. He bases this chiefly on the fact that if volcanic dust is a main factor in causing a reduction of temperature, years showing a large minus departure of temperature ought to be more numerous than years showing a large plus departure. The contrary is the case.

Arctowski's chief result has to do with his so-called pleions and anti-pleions. These, as readers of the *Bulletin* will remember, are the two phases of cycles of about two to four years in length during which the temperature of such places as Arequipa, which is taken as the standard, ranges from about half a degree Fahrenheit above normal during a pleion to half a degree below during an anti-pleion. In his new work Arctowski shows that these pleions are found consistently in large portions of the world, but in some cases they are synchronous with those of Arequipa, elsewhere they lag behind, and in still other places they are reversed. The agreement between widely remote places is so unmistakable that it seems hard to doubt the author's conclusion that we are here dealing with a phenomenon which is due to some non-terrestrial source which acts upon all parts of the earth. The sun is the only known body which could so act. The effect, however, is not the same in all places. For example, suppose that the sun's radiation increases for a few months during the summer of the northern hemisphere. The south polar regions will scarcely be influenced. The oceanic regions directly along the Tropic of Cancer will be heated to an unusual degree, and so will the great continental interiors of North America and Eurasia. On the oceans the heating of different regions in the same latitude will be comparatively uniform, and the excess of heat will be carried away by currents of wind and air in such fashion that the regions to leeward will receive their maximum amount of heat later than the Tropic, although the general character of the wave will be the same. On a continent, because of the great variety of topography and the unequal distribution of cloudiness and other conditions, some particular portion will receive a maximum addition of heat. That region will form the center of one of Arctowski's pleions.

From such a center, for reasons which are not yet understood, the pleion moves to other portions of the continent. It swings around in various directions. In one case the maps show that it started in the south Atlantic states, swung north into Canada, westward nearly to the Pacific coast and south toward upper California. Then it turned around and came back by nearly the same path, and finally swung west into Texas. A pleion may grow in intensity, or may decrease and die out. Several may exist upon a continent at the same time, according to the local circumstances and the season, which determine what places shall be especially heated. At some times a pleionian area, that is an area of temperature higher than the normal, extends all over a continent, or stretches from America across to Europe.

The essential point in Arctowski's researches is this: he has shown that our variations of weather from year to year are not accidental. They follow well-defined laws, and it is only a matter of time, patience and money to trace out the laws and determine in what direction an area of excessive temperature or of high pressure, or of unusual precipitation is likely to move. It ought ultimately to be possible to predict the course of such movements just as the movements of storms are predicted. In addition to this, Arctowski's work seems to show that in the little pleionian cycle, unlike the sun-spot cycle, there appears to be a direct response to variations in the solar radiation. In order to harmonize the conflicting evidence of the large and small cycles it seems necessary to suppose that the sun exerts two distinct kinds of influence. In the first place, changes in its constant of radiation produce the effect that we should normally expect, except that the effects are localized according to the seasons and according to topographic peculiarities. Hence they do not influence all places alike, but are especially prominent in some places and then are propagated outward in the form of irregular waves. Presumably the same thing happens in both the eleven-year and the shorter cycles. It has not been detected in the larger cycle, however, which may be because its effects are neutralized by the other type of solar influence, or because the matter has not yet been studied by Arctowski's geographic method. In the second place, as suggested above, the sun-spots may be connected with some other kind of influence, such as changes in the amount of air carried up in the centers of convectional storms, which may not only neutralize but actually reverse the effect of variations in radiation.